TECTONICALLY CONTROLLED METHANE ESCAPE IN LAKE BAIKAL

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Abstract: Methane, which is at least partly stored in the bottom sediments of Lake Baikal as gas hydrates, is released on the lake floor in the deeper parts of the basin along major faults, forming venting structures similar to small mud volcanoes. The CH_4 venting structures are considered to be the surface expression of escape pathways for excess CH_4 generated by the dissociation of pre-existing hydrates. The existence of a local heat flow anomaly associated with the seep area is most likely due to a heat pulse causing the dissociation of the underlying gas hydrates. The heat pulse may be caused by upward flow of geothermal fluids along segments of active faults, possibly accelerated by seismic pumping. It is assumed that this fluid flow is tectonically triggered, considering that left-lateral strike-slip movements along the border faults act as a major factor in fluid accumulation: even a reduced lateral displacement is able to generate fluid flow in the compressional direction, resulting in fluid escape along faults directed along the main direction of extension. The tectonic effect may be coupled to the sediment compaction due to a high sedimentation rate in the area of mud volcanism. Both processes may generate a large-scale convective fluid loop within the basin-fill sediments which advects deeper gases and fluids to the shallow sub-surface. Even in the extensional tectonic environment of Lake Baikal, local compressional forces related to a strike-slip component, may play a role in fluid flow, accumulation and gas escape along active faults. The mechanisms that result in the expulsion of the CH_4 in the Lake Baikal sediments are considered as an analogue of what could happen during CO_2 sequestration in a similar tectonic environment.

Key words: Methane escape, mud volcanism, gas hydrates dissociation.

S. Lombardi et al. (eds.),
Advances in the Geological Storage of Carbon Dioxide, 203–219.

1. INTRODUCTION

The Baikal rift basin is commonly associated with active extensional tectonics (Logatchev, 1993; Zonenshain et al., 1992; Mats, 1993). The present-day tectonic activity is confirmed by GPS-measurements: the basin undergoes active extension along a WNW-ESE direction with a velocity of up to 4-5 mm/year (Calais et al., 1998; Petit et al., 1997, 1998). Active subsidence is testified by the three large water-filled sedimentary basins comprised by Lake Baikal. Within these basins, active fluid flow results in local heat-flow anomalies (Poort and Klerkx, 2004) and fluid escape at the lake floor (Granin and Granina, 2002; De Batist et al., 2002; Van Rensbergen et al., 2002; 2003). Gas venting has been shown during recent years to be a common phenomenon (Fig. 1).

Methane gas, which has accumulated in the sedimentary infill due to microbial decomposition of organic matter and which is -at least partly- stored as gas hydrates, is released on the lake floor along major fault zones. Reflection seismic profiles have also revealed that the bottom-simulating reflector (i.e. BSR; commonly considered to represent the base of the gas-hydrate stability zone (GHSZ), or -more precisely- the transition between gas-hydrate bearing sediments above and free-gas containing sediments below) has an irregular behaviour, instead of displaying a regular pattern and mimicking the lake floor as it is usually the case. Locally, the BSR is disrupted along faults and vertical fluid-migration conduits that develop along these faults propagate into the GHSZ and extend up to the lake floor. Morphological evidence of fluid escape at the lake floor is given by venting structures, similar to small mud volcanoes. These mud volcanoes appear to be sourced from the base of the GHSZ in areas where the BSR displays an irregular behaviour (De Batist et al., 2002; Van Rensbergen et al., 2002; 2003). Such venting structures occur in several places throughout the lake and their present activity is testified by hydroacoustically observed “plumes” above several of them and an increased concentration of dissolved methane in the bottom water in their vicinity.

Fluid flow in the sediments of Lake Baikal is thus believed to result in the local accumulation of gas (i.e. at the base of the GHSZ) and its subsequent release along zones of weakness. This fluid flow is assumed to result -at least partly- from the tectonic processes that act within the basin. But what are exactly the processes responsible for the destabilisation of gas hydrates and the generation of free methane? What is the tectonic control on methane escape from the lake floor in a tectonic basin under extension? The mechanisms that result in the expulsion of methane present in the Lake Baikal sediments are considered as a natural analogue of what could happen during CO_2 geological sequestration in a similar tectonic environment.

Figure 1. Overview map of Lake Baikal, with indication of the extent of the hydrate province and of the location of mud volcanoes, and of active deep-water and shallow-water seeps.

2. STRUCTURAL OUTLINE OF LAKE BAIKAL AND THE VENTING STRUCTURES

Lake Baikal consists of three distinct bathymetric basins: the South Baikal (SBB), Central Baikal (CBB) and North Baikal basins (NBB). Each of these also corresponds to a well-defined sedimentary basin, bounded by steep border faults, which are best expressed along the northwestern side of the rift. The three basins are at least moderately asymmetric and tend to adopt a half-graben shape (Zonenshain et al., 1992 ; Hutchinson et al., 1992 ; Scholz et al., 1993). They are separated by active high-relief morphostructural ridges, or accomodation zones s.l.. The Selenga Delta Accomodation Zone consists of a broad bathymetric saddle between the SBB and CBB. Although the saddle is largely obliterated by the Selenga delta sediments, it is underlain by several elevated basement blocks (Hutchinson et al., 1992 ; Zonenshain et al., 1992 ; Colman et al., 1993 ; Scholz et al., 1993) (Fig. 1).

The area south of the Selenga delta is complicated in its central part by the Posolsky Bank, a morphological ridge, striking SW-NE, transverse to the basin shape (Fig. 2). It is assumed to be a large back-tilted fault block, belonging to the Selenga Delta Accomodation Zone (Scholz and Hutchinson, 2000) and separated at its south-eastern side from the SBB by a relatively narrow fault zone with a vertical displacement of about 900 m. The south-eastern limit of the Posolsky Bank is delimited by a steep slope corresponding to the Posolsky fault transiting abruptly to the deep-water SBB at depths of about 1100 m. The basin floor gradually deepens to about 1300 m when reaching the steep slope of the main eastern border fault. The sediments of this deep basin are not affected by major faults (Logatchev, 1993 ; Zonenshain et al., 1992 ; Mats, 1993).

The venting area is located immediately south of the structural high of Posolsky Bank. It is delimited at its northern side by a small, secondary fault, antithetic to the Posolsky fault (Fig. 3) (Van Rensbergen et al., 2002). The venting structures are aligned almost parallel to the small antithetic fault (Fig. 2), which offsets the lake floor by about 20 m. Some of the venting structures themselves are also faulted.

The present or recent activity of the venting structures is testified by the freshness of their morphology as observed on side-scan sonar mosaics (Fig. 2), and by the presence of 10-25 m high acoustically non-transparent plumes in the water column above them or along their rims. The venting structures coincide with "gas chimneys"-or fluid-flow conduits- (Figs. 3 and 4) in the sub-surface that are observed on several seismic profiles (e.g. Van Rensbergen et al., 2002; 2003).

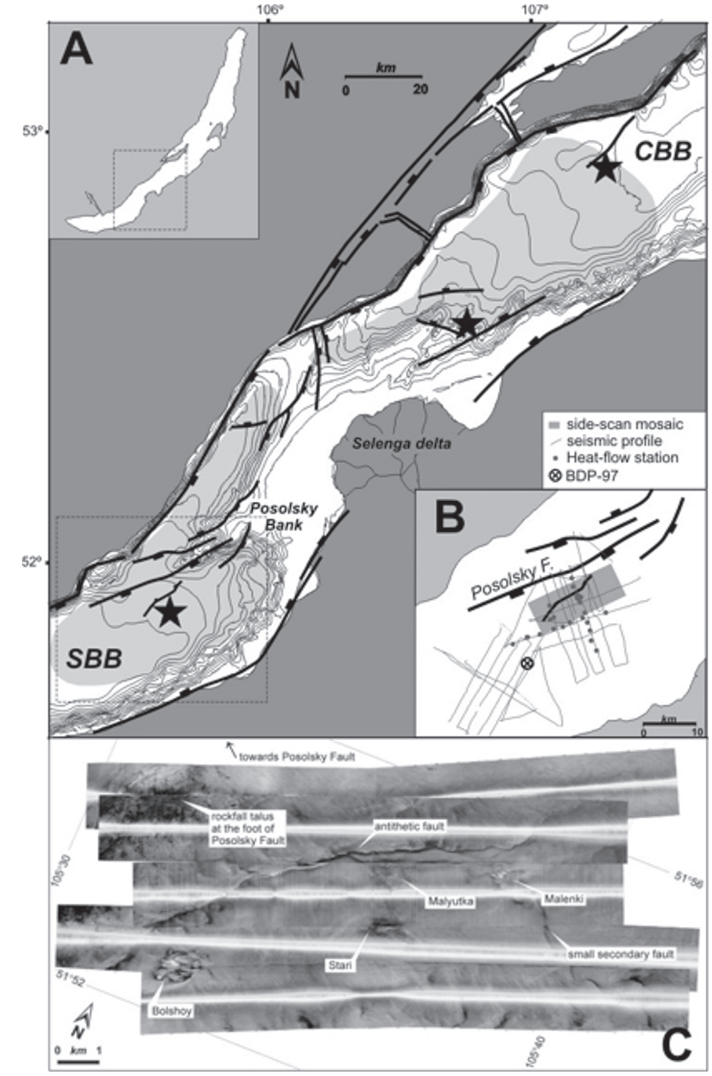

Figure 2. Location map of the study area within the SBB near the Selenga River delta, showing the bathymetry and the main faults (Scholz & Hutchinson, 2000; Mats et al., 2000). The area with inferred hydrate occurrences in the SBB and CBB (Golmshtok et al., 1997) is indicated in grey. Stars indicate areas with anomalously shallow and disrupted BSR and/or with mud volcanoes. A: General location of the study area within Lake Baikal. B: Available data from the Posolsky Bank study area. C. Side-scan sonar mosaic of the Pososlky Bank venting area, with clear indication of the venting structures (i.e. Bolshoy, Stari, Malyutka and Malenki).The venting area is located immediatelhy south of the structural high of Posolsky Bank. It is delimited at its northern side by a small, secondary fault, antithetic to the Posolsky fault (Fig. 3) (Van Rensbergen et al., 2002). The venting structures are aligned almost parallel to the small antithetic fault, which offsets the lake floor by about 20 m. Some of the venting structures themselves are also faulted.

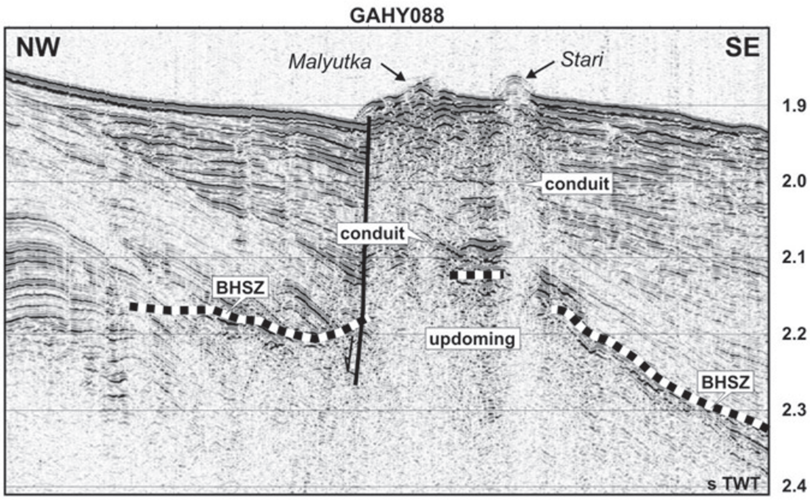

Figure 3. Seismic profile GAHY088 crossing the Stari and Malyutka venting structures, showing the irregular behaviour of the "BSR" and the presence of fluid-flow conduits adjacent to the small fault.

3. METHANE ESCAPE AND ITS RELATION TO BSR AND HEAT FLOW ANOMALIES

A distinct BSR is evidenced in the area south of the Selenga delta on single-channel high-resolution seismic reflection profiles (Vanneste et al., 2000; De Batist et al., 2002). Outside the venting area, the BSR runs regularly and smoothly at a predictable sub-bottom depth, in agreement with the gradually deepening lake floor. In the venting area, the BSR no longer mimics the lake floor, but it becomes highly disrupted and rises to a very shallow sub-bottom depth (figs. 3 and 4) (De Batist et al., 2002).

Intra-basin faults in Lake Baikal generally do not affect the continuity of the BSR or the thickness of the hydrate-bearing layer: the BSR simply cuts across the folded and faulted stratigraphic reflections (Golmshtok et al., 1997). The irregular pattern of the BSR and its disruption suggest the presence of very localized, drastic variations in one or more of the variables controlling the depth of the hydrate phase boundary: i.e. temperature (higher than average), pressure (lower than average) or gas composition. Pressure as a controlling factor can be ruled out as it is difficult to invoke a mechanism by which sub-bottom pressures would be generated that are lower than the background hydrostatic pressure. Heat-flow values in the studied area, determined using marine thermoprobe measurements of the temperature gradient and conductivity in surface sediments, are generally slightly higher (between 55 and 90 mW/m^2, locally up to 165 mW/m^2) than the average heat-flow values for the Baikal Basin which are about 50-70 mW/m^2 (Duchkov et al., 1999). This indicates that the irregular morphology of the BHSZ is predominantly temperature-controlled and directly related to the existence of a local anomaly of high heat flow.

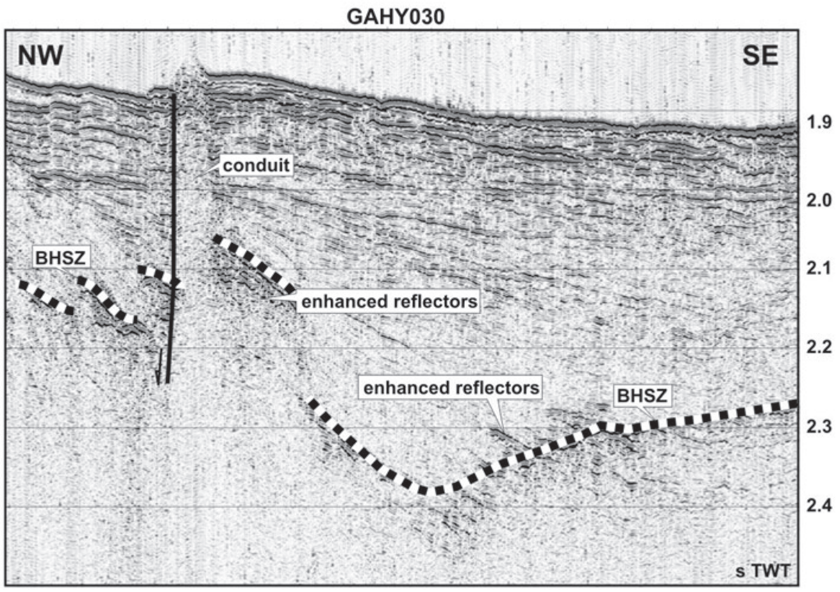

Figure 4. Seismic profile GAHY030 across the small antithetic fault and the adjacent Malenki mud venting structure, showing the strongly disrupted "BSR" and the acoustically chaotic zone extending to the lake floor and affecting the lake-floor morphology.

As the lake-floor venting structures in the deeper parts of Lake Baikal only occur in areas of anomalously shallow and disrupted BSR, characterised by an anomaly of high heat flow, it is concluded that they are the surface expression of escape pathways for excess methane generated by the dissociation of pre-existing hydrates. Moreover, as the gas-venting structures are spatially associated with active faults, it is postulated that gas escape is favoured by the presence of these faults. The fact that the gas-venting structures appear to be confined to particular segments of active faults, suggests that upward fluid flow along the fault plane may have been facilitated by recent dilatation ("leakage") along that segment. Given the fact that the hydrate province in Lake Baikal is located in an active tectonic region, such a process of tectonically driven upward fluid flow and temperature-induced destabilization of hydrates may occur quite regularly, but along different segments of the various active faults.

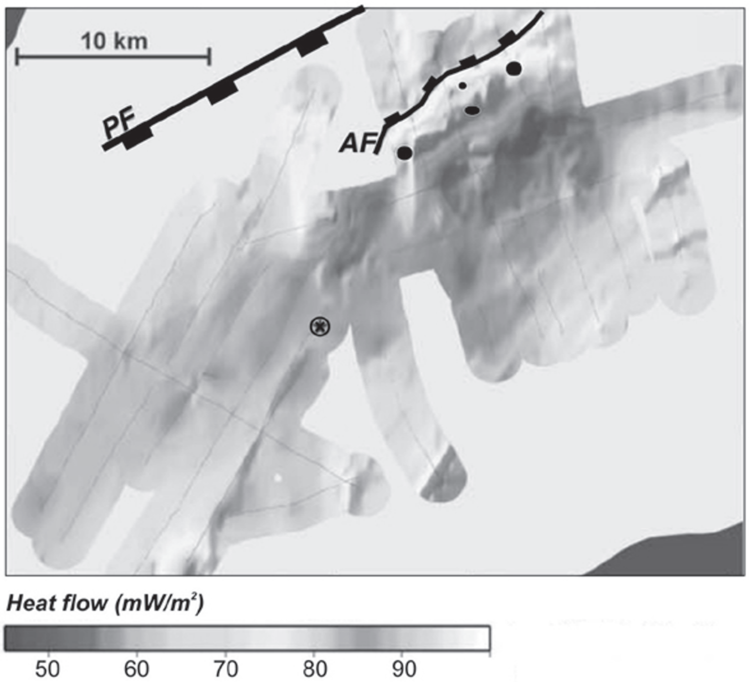

Figure 5. Regional contour map of the BSR-derived heat flow for the Posolksy Bank area (after Vanneste et al., 2003), showing that the localized heat-flow high in the venting area is flanked by a prominent heat-flow low towards the south.

As the position of the BSR, which in general mimics the lake-floor topography, is primarily controlled by temperature, it can be used to estimate the local geothermal field, and consequently to construct a regional contour map of the heat flow (Fig. 5) (Vanneste et al., 2003). This map shows the irregular pattern of the heat flow, with in particular positive anomalies over the venting area, flanked to the south by an area of very low heat flow. However, when comparing the heat flow inferred from the BSR with direct heat-flow measurements, it appears that deviations between measured and inferred heat flow are up to 40 %. The measured heat flow ranges from 56 up to 165 mW/m^2 and is consistently higher than background values.

Maxima are located on the venting sites. The concentric shape of the thermal anomaly with heat-flow values of twice the background heat flow in the venting sites is typical for the focused upward flow of warm fluids (Fig. 6).

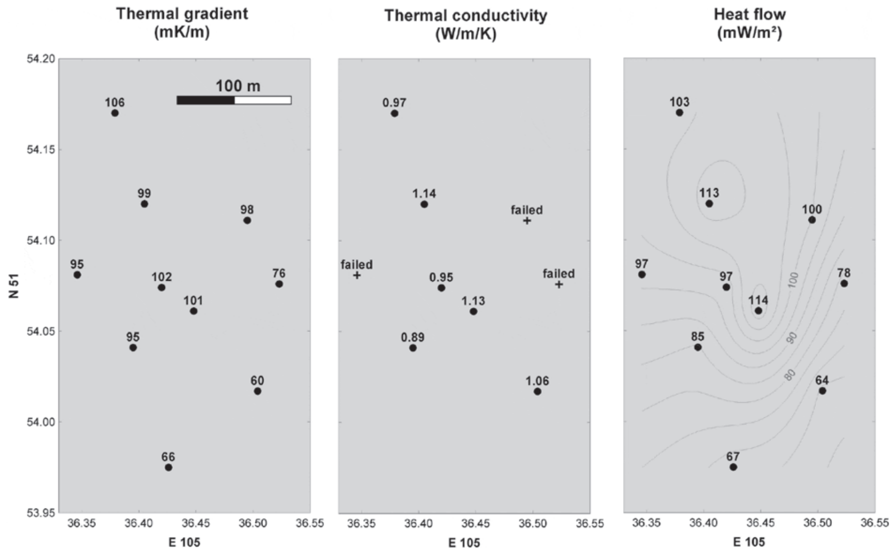

Figure 6. Lateral distribution of the thermal gradient, thermal conductivity and heat flow in and around the Stari mud volcano.

4. INTERPRETATION ON THE ORIGIN OF THE METHANE ESCAPE STRUCTURES

4.1 Presence of a convective fluid flow system

The discrepancy that is locally observed between measured and inferred heat flow implies that the conditions at the surface or/and at the BHSZ are in a non-equilibrium state. Only heat transport by fluid flow is believed to be strong enough to create heat-flow differences of 20-50 % between surface and BSR-depth. In addition, fluid flow is the only process, which can ultimately explain a strongly reduced heat flow at the BSR-depth. This fluid flow has to be downward and active only at BSR-depth. In general, in sedimentary basins fluids are expelled upwards, driven by compaction. Therefore, downward flow demands a driving force which is opposite the compaction and stronger. This force can be delivered by density differences in the fluids and will result in local convection loops.

A conceptual model for a convective fluid loop that accounts for both the positive heat-flow anomalies near the venting sites and the negative heat-flow anomalies zone south of the venting sites, has been proposed (Fig. 7) (Vanneste et al., 2003). The density differences necessary for such a loop can be generated by gas-driven pumping or by lateral density differences by isothermal sea-floor bathymetry.

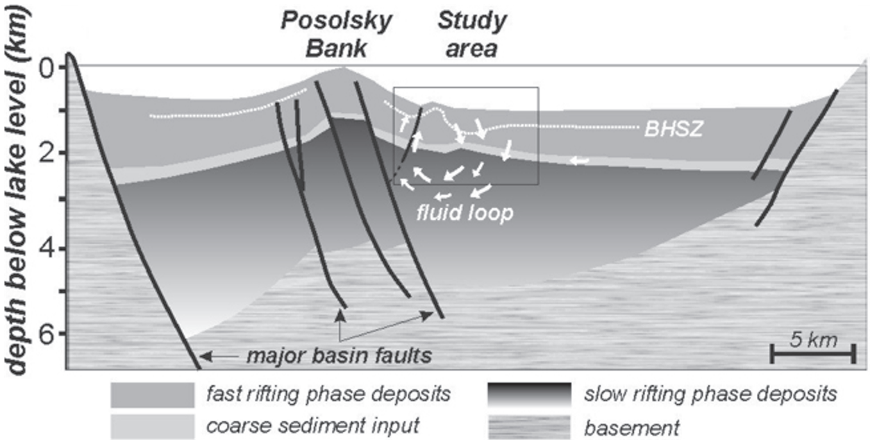

Figure 7. Conceptual fluid-loop model for explaining the characteristic heat-flow signature in the Posolsky Bank study area (after Vanneste et al., 2003).

4.2 Destabilisation of gas hydrates

The cold methane seeps in Lake Baikal are associated with expulsion of sediment which is the result of increase of pore-fluid pressure in the sub-surface to lithostatic values, initiating hydraulic fracturing of the overburden and fluid expulsion. The origin of gas and pore-fluid overpressure appears to be the rapid increase of pore-fluid volume caused by the disintegration of gas hydrates.

Methane seeps are often interpreted to result from gas- and fluid-release by gas-hydrate destabilization in response to various processes. However, gas-hydrate dissociation alone is usually not sufficient to explain methane seepage, as has been shown for example, at the Blake Ridge gas-hydrate area (Paull et al., 1995): gradual decomposition of hydrates at the base of the hydrate layer is insufficient to account for the estimated upward fluid flow (Egeberg, 2000) and, consequently, for the methane released at the sea floor.

In Lake Baikal, the existence of a local anomaly of high heat flow associated with the seep area is most likely due to a heat pulse causing the dissociation of the underlying gas hydrates. The heat pulse can be caused by upward flow of geothermal fluids along active segments of the Posolsky fault, maybe accelerated by seismic pumping. The elevated heat flow is probably transient as it is related to fault activity that may jump to other segments of the fault, possibly causing destabilization of hydrates, seeps, and mud volcanoes elsewhere in the basin (Van Rensbergen et al., 2002).

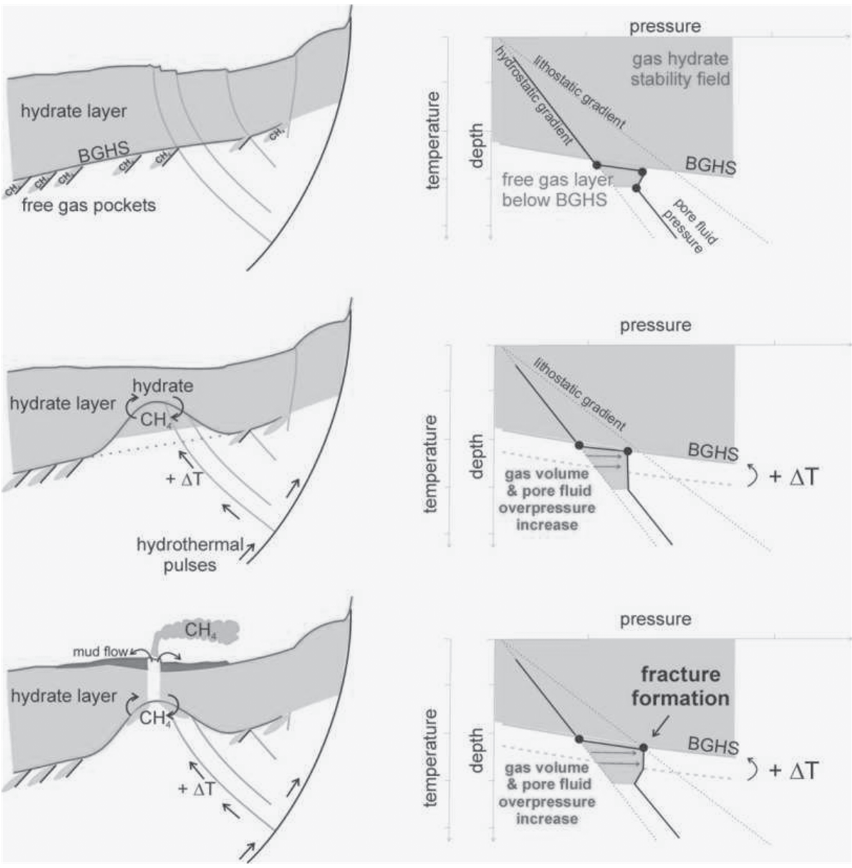

Figure 8. Schematic model explaining the localised destabilisation of gas hydrates in response to a structurally guided upward flow of fluids advecting heat to the BHSZ, creating an overpressure compartment and leading to the expulsion of remobilised sediment and fluids at the lake floor as gas seeps and mud volcanoes (after Van Rensbergen et al., 2003).

4.3 A tectonic driving force

Among the processes that may be involved in the shallowing of the base of the GHSZ, the destabilization of the gas hydrates and the upward channeling of fluids (Dillon et al., 1998; Henriet and Mienert, 1998; Tréhu et al., 1999), only two are relevant to the specific sedimentary and tectonic environment of Lake Baikal: compaction-driven fluid flow and tectonically driven fluid flow.

- *Compaction-driven fluid flow* may indeed play a role, as the area south of Selenga delta is the site of major sediment input in the lake. On the Selenga delta the sedimentation rate for the last 30,000 years is between 15 and 19 cm/kyr (Colman et al., 1996). When the sedimentary section is rapidly thickening by sedimentation, the GHSZ shifts upward continuously destabilizing gas hydrates at its base. Free gas consequently accumulates from the dissociation of the gas hydrates (von Huene and Pecher, 1999). When a fault reaching the base of the GHSZ is reactivated, this fault can tap the area of fluid accumulation underneath the BSR allowing the fluids to discharge along the fault and to reach the lake floor. Fluids ascending from below the BSR are warmer than the surrounding sediments, which results in destabilization of gas hydrates and upward migration of the BSR. Such a process has been proposed for the Cascadia convergent margin (Suess et al., 1999). The presence of mud volcanoes in the Black Sea (Limonov et al., 1997), under an extensional regime, also is interpreted by fast subsidence and burial of mobile source beds resulting in overpressure. But the high rapid sediment accumulation doesn't account for the irregular behavior (i.e. the combined occurrence of areas with shallower-than-background and deeper-than-background BSR) of the BSR.
- *Tectonically driven fluid flow,* by fluid flow along fault conduits, has been sufficiently documented for playing a role in the destabilization of gas hydrates in the compressional environment of active continental margins (a.o. Booth et al., 1998; von Huene and Pecher, 1999; Suess et al., 1999).

Even in the extensional tectonic environment of Lake Baikal, local compressional structures have been observed. Levi et al. (1997) emphasizes folding structures affecting the sedimentary section in the western part of the SBB, consisting of NW-SE trending folds with up to 1 km amplitude and 7-8 km wavelength. The folded structures are attributed either to a phase of horizontal principal compression in a NE-SW direction, parallel to the longitudinal axis of the basin, or -more probably- to strike-slip movements. Folding of the sedimentary section also has been evidenced on many seismic sections obtained in the SBB and CBB by Golmshstok et al. (2000), who relate these folding structures to movements along strike-slip faults. Their axes are considered to be almost orthogonal to the axis of the basin. Also a prominent roll-over structure is evidenced in the eastern part of the central basin (Moore et al., 1997). This roll-over structure is considered to have developed at the western side of a strike-slip fault zone which extends over more than 50 km in the CBB.It is interesting to note that the fold axes have a WNW trend. On the contrary, the axes of depocentres for several depositional stages trend NNE, oblique to the main fault structures.

Evidences for a left-lateral strike-slip component in the main extensional kinematics of the Baikal basin consequently exist, the axes of compression varying between WNW in the CBB and NW in the extreme south of the SBB. Although the significance of the strike-slip movement for the tectonic evolution of the Baikal basin is not fully understood, it is evident that it plays a role in the deformational pattern of the sedimentary fill.

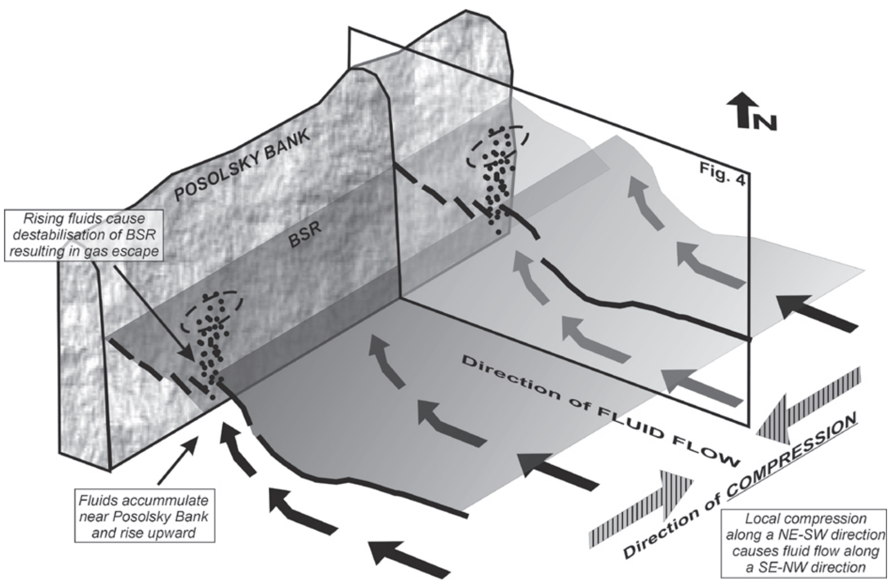

Figure 9. Schematic diagram showing the fluid flow that is generated along the NW-SE trending compression related to NE trending strike-slip movement. Fluids accumulate against Posolskii Bank, resulting in updoming of the BSR and CH_4 escape along NE trending extensional faults.

The left-lateral strike-slip movement that has been evidenced results in shortening of the sedimentary layers and dewatering of the sediments, and consequently generates a fluid displacement. The direction of fluid transport should be NW, orthogonal to the direction of principal compression which is

NE-SW. As this direction corresponds to the progressive shallowing of the BSR, we propose that fluids are moving northwestwards along the sedimentary layering in the fluid-enriched zone underneath the base of the GHSZ. The basement block of Posolsky Bank forms a barrier for the moving fluids. When approaching this barrier, the amount of fluids progressively increases and their heat supply results in upward movement of the BSR. Close to Posolsky Bank, fluids will consequently concentrate, creating overpressure that results in thermal up-doming and finally disruption and destabilisation of the gas-hydrate layer. When a fault oriented along the NE-SW major direction of extension will be activated, the BSR is disrupted and fluids erupt along this fault. Also in the other areas of known mud volcanism in Lake Baikal, the mud volcanoes and methane escape occur along major extensional intra-basin faults trending NE-SW.

Although the rapid sediment accumulation in the area of the Selenga delta may play a role in the process of fluid accumulation, it is assumed that fluid flow induced by left-lateral strike-slip movements along the border faults is a major factor for the fluid accumulation, which is responsible for up-doming and destabilization of the base of the GHSZ, and consequently generation of methane and its escape on the lake floor.

5. DISCUSSION AND CONCLUSIONS

Active escape of methane and/or other fluids - i.e. cold seeps – occurs at several locations on the lake floor of Lake Baikal, forming mud volcanoes which involve not only methane/fluid seepage into the lake water, but also mobilize and expulse sub-surface sediment. In all cases, methane venting occurs along well-constrained segments of active, first-order rift-basin faults. Moreover, the areas of mud volcanism are always underlain by gas hydrates in the sub-bottom sediments.

A tentative model is proposed which relates the methane released at the lake floor in the seep areas, as well as the associated expulsion of re-mobilized sub-surface sediments, to the destabilization of gas hydrates at the base of the hydrate-bearing sediment section. This destabilization - involving the disruption of the BSR, a localized shallowing of the BHSZ, and the generation of an overpressure compartment - must have occurred in response to an upward flow of geothermal fluids, advecting heat to the BHSZ. It is assumed that this fluid flow is tectonically triggered, considering that even in an extensive tectonic environment, a reduced lateral displacement component is able to generate a fluid flow in the compressional direction, resulting in fluid escape along faults directed along the main direction of extension. The tectonic effect may be coupled to the sediment compaction due to a high sedimentation rate. Both processes may generate a large-scale convective fluid loop within the basin-fill sediments which advects gases and fluids of deeper origin to the shallow sub-surface within the upward-flowing limb of this fluid loop.

Is methane escape on the lake floor of Lake Baikal presenting analogies with gas release in the process of CO_2 sequestration? There are major differences between the natural occurrence of methane venting in Lake Baikal, related to destabilisation of gas hydrates, and the processes involved in CO_2 sequestration: in Lake Baikal, only methane is released on the lake floor, and moreover, strong overpressure is created when huge amounts of methane are liberated when gas hydrates dissociate. Nevertheless, the tectonic processes resulting from local compression that are supposed to play a role in fluid-flow generation in Lake Baikal, as well as the role of sediment compaction due to a high sedimentation rates, may also be effective in the processes of CO_2 sequestration.

Heat flow anomalies may be an indicator of such processes. It is clearly evidenced in the area of mud volcanism in Lake Baikal that the gases ascending from depths are accompanied by fluids that are warmer than the environment where they escape, and that they create local heat flow anomalies. These heat flow anomalies are consequently an indicator of intensive, even cold gas and fluid seepages when the fluids generate at a sufficient depth.

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